Simplified Models for Plume Dynamics

Simulation Studies for Geological CO_2 Storage Certification Framework

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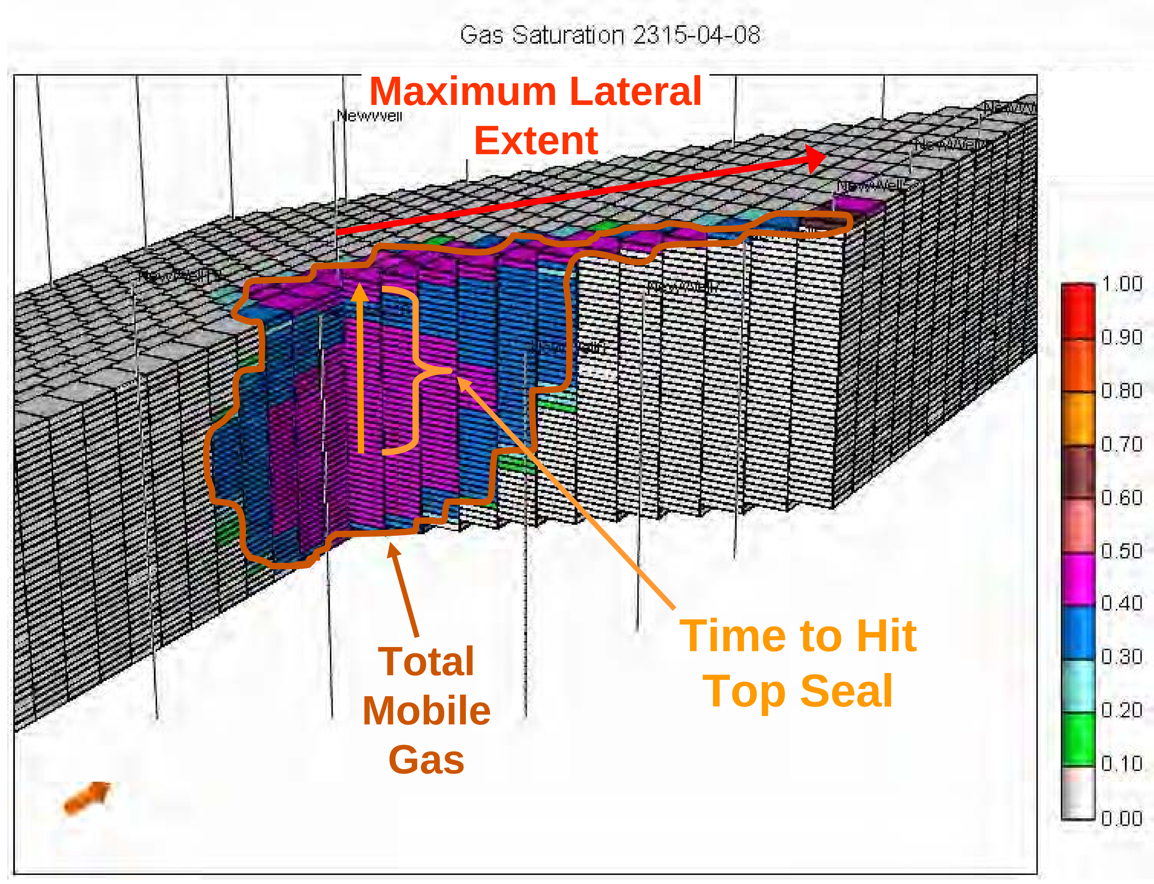
ABSTRACT

Simplified models of CO_2 plume dynamics are needed for a certification framework for geological CO_2 storage. 3D simulations of buoyancy driven flow were conducted. We characterized the effect of reservoir and operating parameters on three response variables—time for plume to reach top seal, maximum lateral extent, and total mobile gas in reservoir—that affect risk of leakage.

BACKGROUND

A critical requirement for large-scale deployment of CO_2 sequestration in brine formations is a framework for certifying and decommissioning sites. As part of the development of such a framework, we are developing simple models and conducting a series of simulations to evaluate ranges of CO_2 plume behavior. It is crucial that the framework be simple and transparent, so we seek the simplest possible description of the key mechanisms.



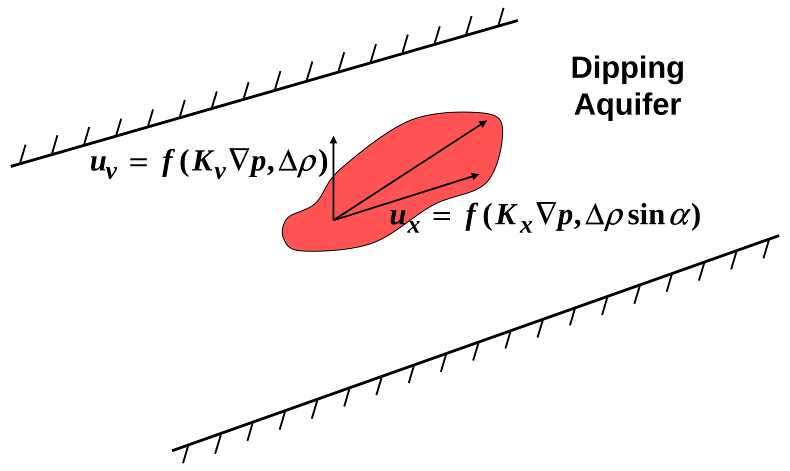
OBJECTIVES

- **Development of simple and transparent framework acceptable to key stakeholders for evaluating the risk of CO_2 leakage on resources and environment**
- **Developing scenarios for the most likely reservoir types to be used for CO_2 storage, modeling and simulation of the scenarios and calculating the associated risks**
- **Deep saline aquifers are primary focus because the range of behavior, parameters, and operating conditions is relatively simpler**

PLUME MOVEMENT IN DIPPING RESERVOIR

- **More lateral movement in updip direction**
- **More trapping due to larger movement**

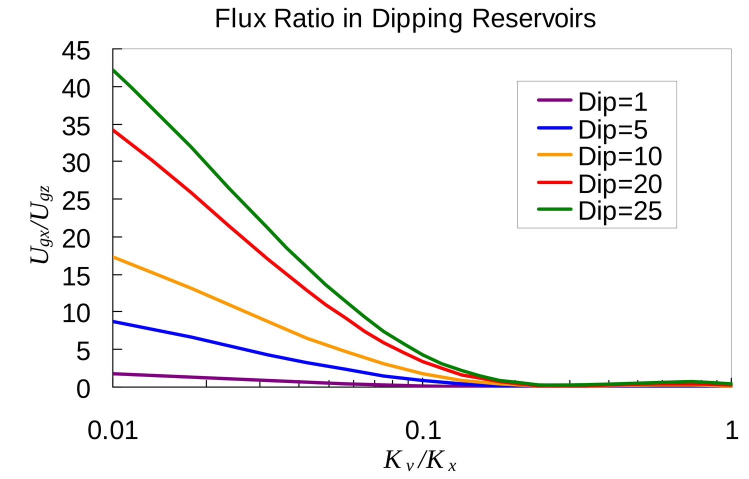
$$\left(\frac{u_{gx}}{u_{gv}}\right)_f = \frac{k_x\lambda_{rw}\left(\Delta\rho g\sin\alpha - \frac{\partial P_c}{\partial x}\right)}{k_v\lambda_{rw}\left(\Delta\rho g - \frac{\partial P_c}{\partial v}\right)}$$

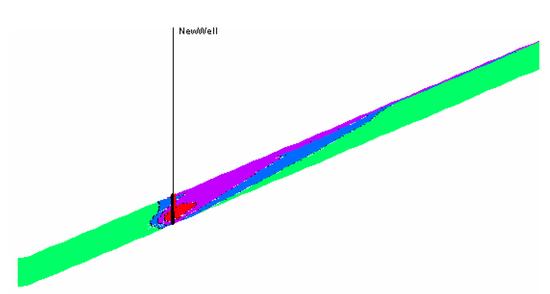


Resultant velocity magnitude and direction

$$u = \sqrt{u_x^2 + u_v^2 + 2u_x u_v \sin\alpha}$$

$$\cos\theta = \frac{u_x + u_v\sin\alpha}{u}$$





EQUIVALENT HOMOGENEOUS MEDIUM TO ACCOUNT FOR SHALE BARRIERS

- **The tortuous path of a buoyant plume around series of shale barriers to vertical movement can be replaced by equivalent homogeneous path having equivalent permeability anisotropy**
- **The equivalent model for time to reach the top seal is shown here:**

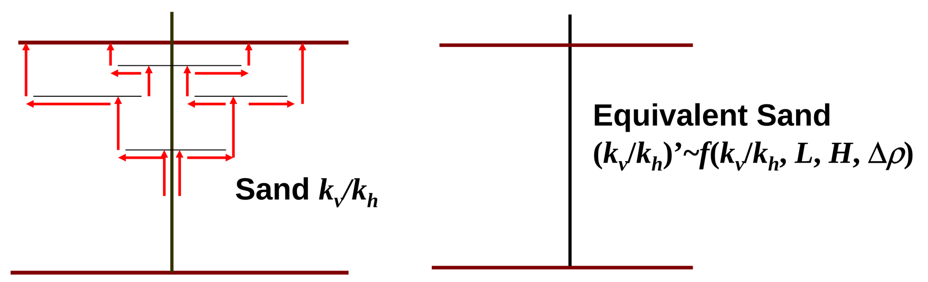
$$\frac{k_v'}{k_h} = \frac{\frac{k_v}{k_h}N_g H}{hN_g + L\left(\frac{k_v}{k_h}\right)\left(1+\frac{\rho_g g}{\partial P/\partial x}\right)N_g + (H-h)\left(1+\frac{\rho_g g}{\partial P/\partial x}\right)}$$

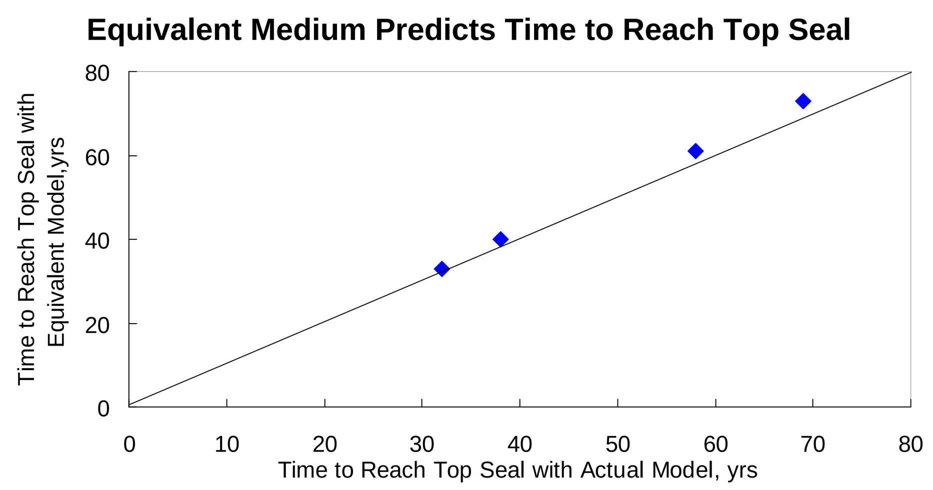
Single Barrier Simulations and Model	Actual		Equivalent	
	k_v/k_h	t^*	k_v/k_h	t^*
L = 2750 ft, h = 17.5 ft, H = 100 ft	0.03	38	0.006	40
	0.01	69	0.003	73
L = 1750 ft, h = 17.5 ft, H = 100 ft	0.03	32	0.007	33
	0.01	58	0.004	61

* Time to hit top seal, years

where

- **H is the height of top seal from perforation**
- **h is the height of shale barrier from perforation**
- **L is the half length of shale barrier**
- **N_g is $\left(\frac{\Delta\rho g}{\partial P/\partial x}\right) = \frac{k\Delta\rho g}{\mu u}$**





RANGE OF INPUT PARAMETERS FOR FRAMEWORK SIMULATIONS

Porosity	0.1	0.25	0.35
Permeability (md)	10	100	1000
Anisotropy	0.001	0.03	1
Thickness (ft)	100	500	1000
Dip	0	5	25
Depth (ft)	10000	5000	2000
Ratio of perforated interval to thickness	1	0.5	0.25

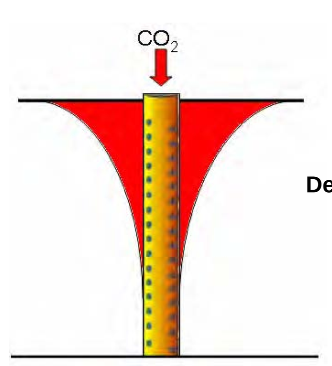
- **Simulations carried out for these combination of parameters and their ranges**
- **Parameter ranges cover most of the potential CO_2 storage aquifers**

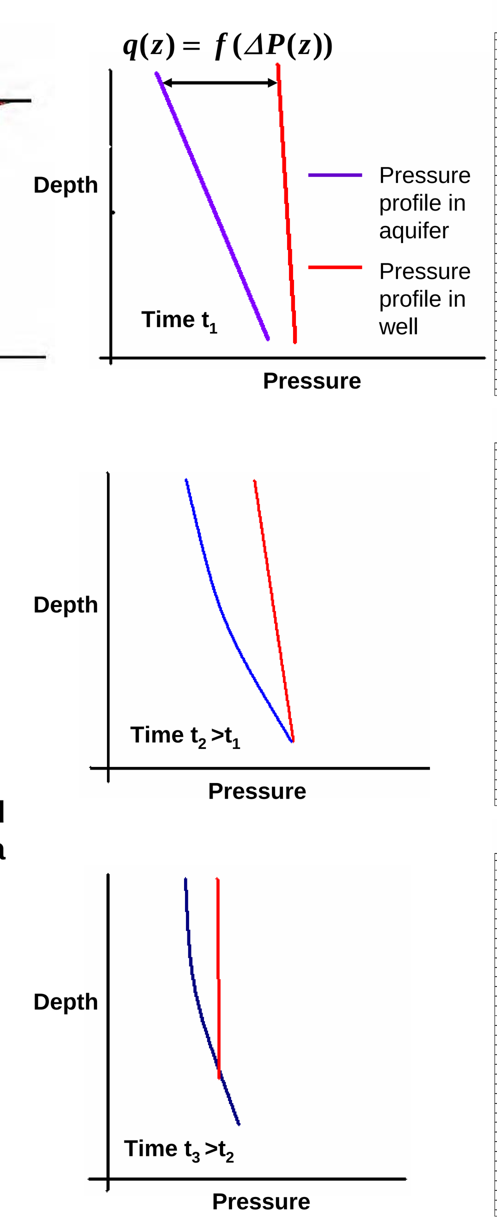
OPTIMUM PERFORATION INTERVAL

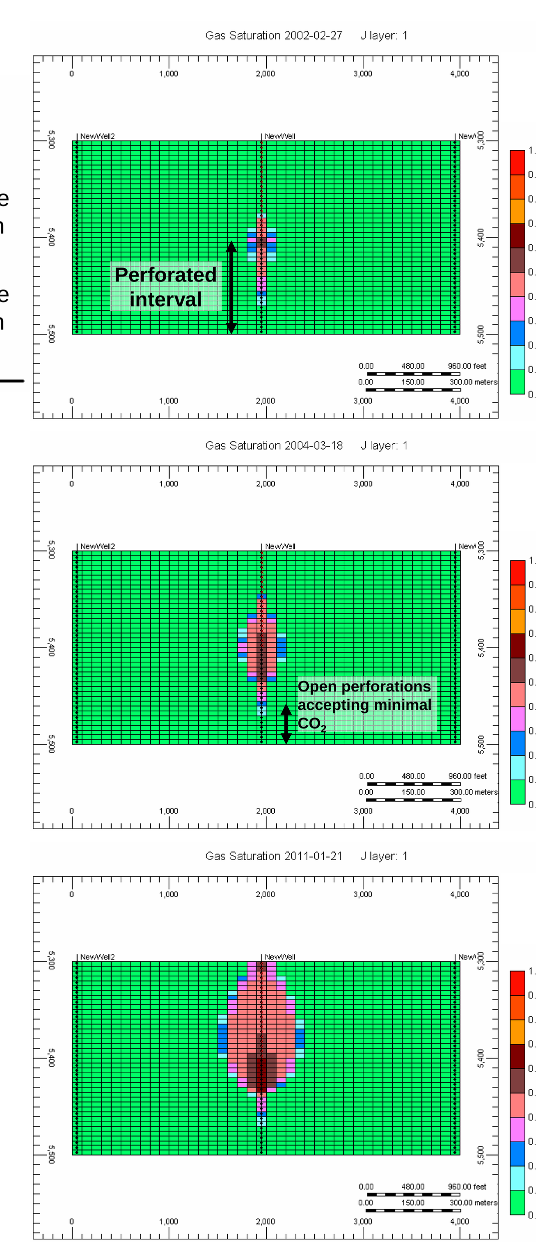
- **Given CO_2 injection rate and aquifer kh, what perforated interval gives longest time to reach top seal?**
- **Difference between hydrostatic gradient in well and in reservoir leads to non-uniform distribution of injected CO_2 along the perforated interval.**
- **At start of injection if $H > z$ (depth at which the pressure curves intersect), all the perforations are active**

$$Q_T = \begin{cases} \int_0^Z dq_{CO_2} = \frac{kk_{rw}}{\mu\ln\left(\frac{r}{r_w}\right)}2\pi\left\{\left(P_{wt}-P_{rt}\right)Z - \Delta\rho g\frac{Z^2}{2}\right\} & \text{if } z \le H \\ \frac{kk_{rw}}{\mu\ln\left(\frac{r}{r_w}\right)}2\pi\left\{\left(P_{wt}-P_{rt}\right)H - \Delta\rho g\frac{H^2}{2}\right\} & \text{if } z > H \end{cases}$$

- **To determine P_{wt}, pressure at well top:**
  - **Start with $P_{wt} > P_{rt}$ and calculate z**
  - **Calculate Q_t**
  - **If Q_t < rate of injection, increase to next higher step and repeat steps 1 and 2; if Q_t > rate of injection, decrease to a lower value and repeat earlier steps.**
- **After a small time period, saturation around well is calculated from the amount of CO_2 injected in incremental volume**
- **Relative permeability and density of reservoir fluid is updated and again the above procedures are followed**
- **The optimum perforation can now be perforated at bottom of reservoir increasing the distance of top perforation from top seal**

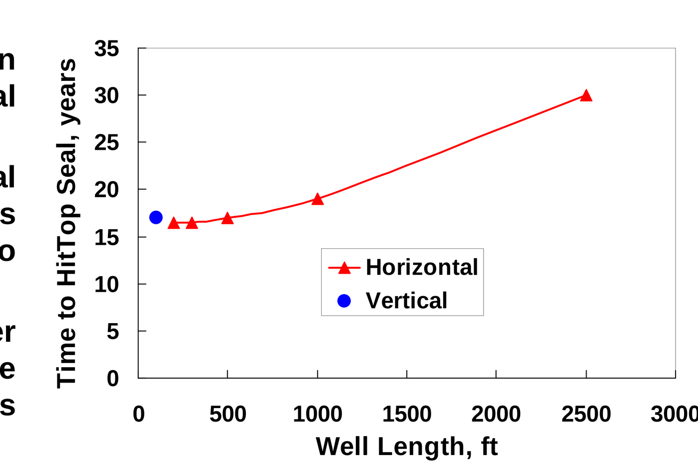


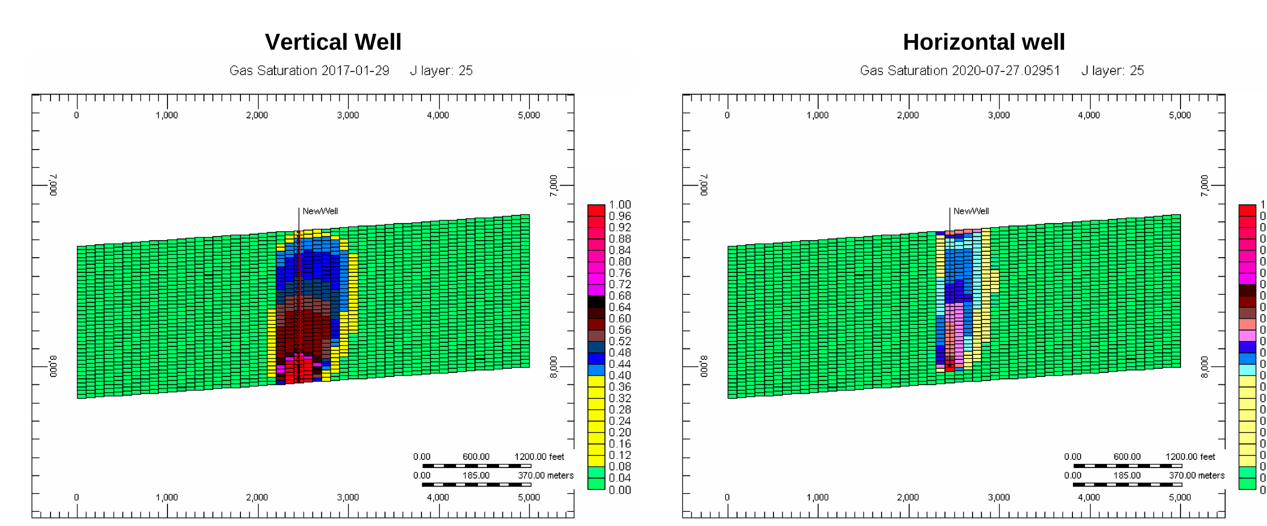




RISK REDUCTION WITH HORIZONTAL WELL vs. VERTICAL WELL

- **The effect of horizontal well vs. vertical well on response variables depends upon horizontal length, vertical permeability, and injection rate**
- **Distribution of total flow along greater horizontal lengths reduces the plume velocity; it increases CO_2 contact with brine and rock compared to vertical well, increasing trapping**
- **On the other hand, due to lower velocity (higher gravity number), gravity force dominates and the flow is almost vertical, thus contacting less brine/rock in horizontal direction**





CONCLUSIONS

- **Certification framework provides simple guidelines to follow while commissioning or decommissioning a geological site for CO_2 sequestration**
- **Operating parameters need to be decided based on requirements and their effects**
- **To some extent, inhomogeneous systems can be replaced by equivalent homogeneous systems**

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